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Four- and three-body breakup mechanism of ^{6}Li elastic scattering

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Abstract. We investigate a breakup mechanism of ^{6}Li elastic scattering on heavy targets (T = ^{209}Bi or ^{208}Pb) with the four-body version of the continuum-discretized coupled-channels method (four-body CDCC). Four-body CDCC successfully reproduces measured elastic cross sections with no adjustable parameter, and we can then clearly discuss the four-body dynamics. Our analysis shows that $d\alpha$ breakup (^{6}Li + T $\to d + \alpha$ + T) is much more essential than $np\alpha$ breakup (^{6}Li + T $\to n + p + \alpha$ + T) in ^{6}Li scattering.

1. Introduction

In reactions of weakly-bound nuclei, projectile breakup plays an important role and the treatment of projectile-breakup effects is essential to describe scattering. The continuum-discretized coupled-channels method (CDCC) was proposed as a method for treating breakup effects [1, 2, 3]. Nowadays, CDCC is applied to not only three-body scattering (two-body projectile + T) but also four-body scattering (three-body projectile + T) [4, 5, 6, 7], where T denotes a target. CDCC for three- and four-body scattering are now called three- and four-body CDCC, respectively.

^{6}Li + ^{209}Bi scattering near the Coulomb barrier energy ($E_{\rm b}^{\rm Coul} \approx 30$ MeV) was first analyzed with three-body CDCC based on the d+α + ^{209}Bi three-body model [8]. However, the calculation could not reproduce the measured elastic cross section without introducing a normalization factor for the optical potentials. This problem was solved by four-body CDCC based on the $n + p + \alpha$ + ^{209}Bi four-body model [6]. The four-body calculation describes the experimental data without introducing any adjustable parameter. As an interesting finding, we showed that three-body CDCC can reproduce the cross section if the phenomenological d-optical potential is replaced by the single-folding potential that does not include d-breakup effects [6]. This suggests that d (*i.e.* the n-p subsystem of ^{6}Li) hardly breaks up during ^{6}Li scattering. In this work, we investigate the breakup mechanism within the four-body CDCC framework and validate the evidence.

2. Decomposition of the CDCC model space

We only recapitulate the treatment of model space in four-body CDCC; see Ref. [3, 7] for the detail. In four-body CDCC, the Schrödinger equation is solved in the model space P spanned by

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the ground and discretized-continuum states of ^{6}Li: $P = \sum_{\gamma=0}^{N} |\Phi_\gamma\rangle\langle\Phi_\gamma|$, where Φ_γ represents the γ-th eigenstate, and the $\gamma = 0$ and $\gamma = 1$–N correspond to the ground and discretized-continuum states, respectively. The Φ_γ are obtained as pseudostates by using the Gaussian expansion method [9].

In this paper, we investigate the breakup mechanism by restricting the model space P. For this purpose, we first specify whether the breakup state Φ_γ ($\gamma = 1$–N) is the $d\alpha$-dominant or $np\alpha$-dominant breakup state by calculating the squared overlap between Φ_γ and the d ground state $\phi^{(d)}$: $\Gamma_\gamma^{(d\alpha)} = \left|\langle\phi^{(d)}|\Phi_\gamma\rangle\right|^2$. If $\Gamma_\gamma^{(d\alpha)}$ is larger (smaller) than 0.5, the state is defined as a $d\alpha$-dominant state $\Phi_\gamma^{(d\alpha)}$ ($np\alpha$-dominant state $\Phi_\gamma^{(np\alpha)}$). With the $d\alpha$- and $np\alpha$-dominant state above, the CDCC model space P can be decomposed into the three parts $P = P_0 + P_{d\alpha} + P_{np\alpha}$, where

$$P_0 = |\Phi_0\rangle\langle\Phi_0|\,,\ P_{d\alpha} = \sum_\beta |\Phi_\beta^{(d\alpha)}\rangle\langle\Phi_\beta^{(d\alpha)}|\,,\ P_{np\alpha} = \sum_\delta |\Phi_\delta^{(np\alpha)}\rangle\langle\Phi_\delta^{(np\alpha)}|\,. \quad (1)$$

In the following discussion, we calculate cross sections by switching on and off to clarify the reaction dynamics.

3. Results

First, we show the validity of four-body CDCC. Figure 1 shows the angular distribution of elastic cross section for ^{6}Li + ^{209}Bi scattering at 32.8 MeV. The three-body CDCC calculation (dashed line) underestimates the experimental data as reported in Ref. [8]. We then apply four-body CDCC in order to explain this discrepancy. Four-body CDCC (solid line) perfectly reproduces the experimental data without introducing any adjustable parameter. ^{6}Li + ^{209}Bi scattering near the Coulomb barrier energy is thus described by four-body CDCC. Therefore, we can clearly discuss the breakup mechanism below.

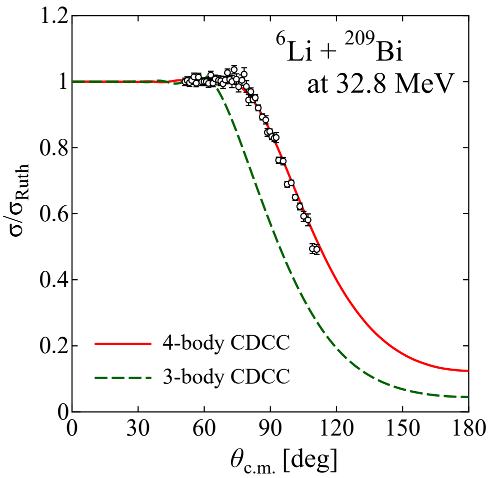
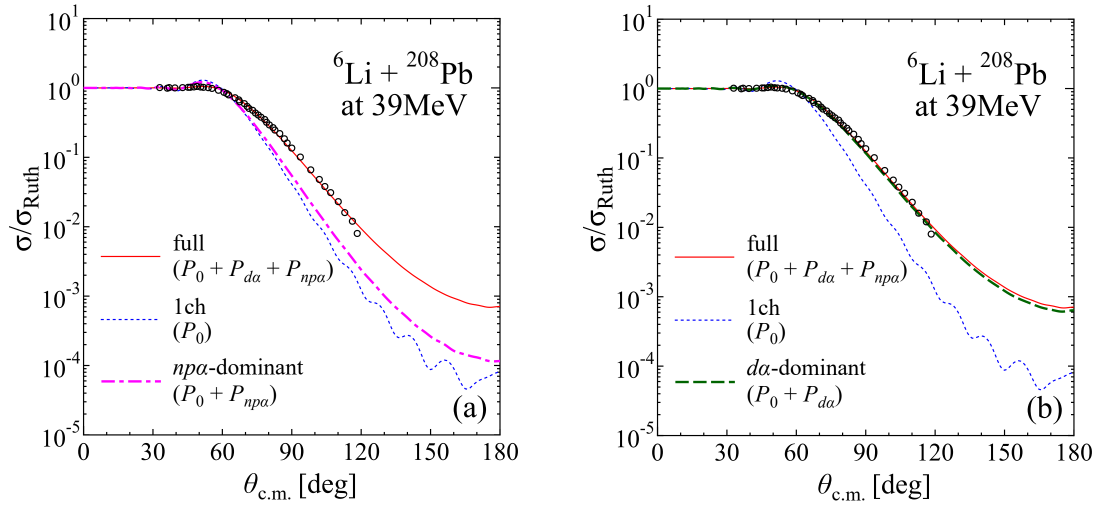


Figure 1. (Color online) Elastic cross sections (divided by the Rutherford cross section) for ^{6}Li + ^{209}Bi scattering at 32.8 MeV. The solid (dashed) line represents the result of four-body CDCC (three-body CDCC) calculation. The experimental data is taken from Refs.[10, 11].

Next, we show ^{6}Li + ^{208}Pb scattering at 39 MeV in Fig 2, which is almost the same as ^{6}Li + ^{209}Bi scattering at 32.8 MeV. The solid and dotted lines correspond to the full and 1ch calculations, respectively. These are nothing but the calculations in P and P_0, respectively. The difference comes from breakup effects and the full calculation reproduces the experimental data well by virtue of breakup effects.

Now, we switch on only the subspace $P_{np\alpha}$ or $P_{d\alpha}$ from P_0 in order to investigate the breakup mechanism. The dot-dashed line (a) represents the calculation of $P_0 + P_{np\alpha}$ and it is close to 1ch calculation (dotted line). On the other hand, the dashed line (b) corresponds to the calculation of $P_0 + P_{d\alpha}$ and it simulates the full calculation (solid line) almost perfectly. It should be noted that the number of $d\alpha$-dominant states is much less than that of $np\alpha$-dominant states in the present model space P. As seen above, $d\alpha$ breakup is favored in ^{6}Li scattering. This property is now called $d\alpha$-*dominance*, and we have found that the $d\alpha$-*dominance* is realized in a wide energy range [7]. It has been thus confirmed that d (*i.e.* the n-p subsystem of ^{6}Li) hardly breaks up during ^{6}Li scattering.



(a) Effects of $P_{np\alpha}$ (b) Effects of $P_{d\alpha}$

Figure 2. (Color online) Elastic cross sections for ^{6}Li + ^{208}Pb scattering at 39 MeV. The solid and dotted lines correspond to the results of full and 1ch calculations, respectively. The dot-dashed line (a) represents the calculation with the model space $P_0 + P_{np\alpha}$, whereas the dashed line (b) shows the calculation with $P_0 + P_{d\alpha}$. The experimental data is taken from Ref. [12].

4. Summary

We have investigated four-body dynamics of ^{6}Li elastic scattering ($n + p + \alpha + \mathrm{T}$, T = ^{209}Bi or ^{208}Pb). The elastic scattering are successfully described in the four-body CDCC framework without introducing any adjustable parameter. We can then clearly analyze the breakup mechanism. Our analysis shows that the $d\alpha$-dominant breakup is much more essential compared with the $np\alpha$-dominant breakup for describing the scattering ($d\alpha$-*dominance*). This justifies the fact that d (*i.e.* the n-p subsystem of ^{6}Li) hardly breaks up during ^{6}Li scattering.

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